

Why are some galaxy disks extremely thin?

Arunima Banerjee^{1*}, and Chanda J. Jog^{2†}

¹ *National Centre for Radio Astrophysics, TIFR, Pune 411007, India*

² *Department of Physics, Indian Institute of Science, Bangalore 560012, India*

1 November 2012

ABSTRACT

Some low surface brightness galaxies are known to have extremely thin stellar disks with the vertical to planar axes ratio 0.1 or less, often referred to as superthin disks. Although their existence is known for over three decades, the physical origin for the thin distribution is not understood. We model the stellar thickness for a two-component (gravitationally coupled stars and gas) disk embedded in a dark matter halo, for a superthin galaxy UGC 7321 which has a dense, compact halo, and compare with a typical dwarf galaxy HoII which has a non-compact halo. We show that while the presence of gas does constrain the disk thickness, it is the compact dark matter halo which plays the decisive role in determining the superthin disk distribution in low-mass disks. Thus the compact dark matter halo significantly affects the disk structure and this could be important for the early evolution of galaxies.

Key words: galaxies: ISM - galaxies: kinematics and dynamics - galaxies: spiral - galaxies: structure - galaxies: halos - galaxies: individual : UGC 7321, HoII

1 INTRODUCTION

The stellar disk in a typical spiral galaxy is thin, as seen from the image of an edge-on galaxy like NGC 4565, and contains most of the visible mass in a late-type galaxy. There is a particular class of galaxies where the stellar disk is extremely thin, the so-called superthin (Goad & Roberts 1981), or flat (Karachentsev 1989) galaxies, where the vertical to radial axes ratio of the galaxy as projected on the sky is 0.1 or less (Matthews et al. 1999), also see Kautsch (2009) for a recent review.

There is no clear physical understanding yet of why the stellar disks in these galaxies are thin. This is of interest for understanding the structure and dynamics of these galaxies. In addition, the superthin galaxies have become interesting recently for two reasons. First, all the superthin galaxies are low surface brightness (LSB) galaxies though the reverse is not true. Thus understanding why these are so thin may help shed light on the overall evolution of LSB galaxies. The LSBs are common, are highly gas-rich yet do not appear to have had a significant star formation, and their origin and dynamics are not understood well (e.g., de Blok 2006). Second, galaxy interactions are now known to be common and can thicken the stellar disks (Walker et al. 1996, Velazquez & White 1999, Qu et al. 2011). Irrespective of what gives

rise to the thick disks, most large galaxies are now known to contain a thick disk (Gilmore & Reid 1983, Dalcanton & Bernstein 2002). In view of this, the existence of galaxies with a superthin stellar disk is even more puzzling.

The vertical thickness of a galactic stellar disk is determined by the balance between the vertical self-gravitational force and pressure (e.g., Rohlfs 1977). The inclusion of gas, despite its low mass fraction, has a significant constraining effect in the determination of the stellar thickness. This is because the gas being a low-dispersion component is located closer to the mid-plane (Narayan & Jog 2002b, Banerjee & Jog 2007). The LSB galaxies are known to be dark-matter rich from the innermost radii of the galactic disk (McGaugh & de Blok 1998, Banerjee et al. 2010). Thus the halo is likely to play an important role in reducing the stellar thickness in these, since the surface density of dark matter within a constant thickness near the mid-plane dominates the disk surface density from the inner regions (see Fig. 3, Banerjee et al. 2010).

In this paper, we study the stellar thickness for a two-component (stars plus gas) disk in a dark matter halo. We study the prototypical superthin galaxy UGC 7321 for which the various input parameters for the stellar and gas components have been determined from observations (Matthews et al. 1999, Matthews 2000, Uson & Matthews 2003, Matthews & Wood 2003). We obtain the stellar scale height at different radii for UGC 7321 using the two-component model of gravitationally-coupled stars and gas in the field of a dark

* E-mail : arunima@ncra.tifr.res.in

† E-mail : cjjog@physics.iisc.ernet.in

matter halo as developed in Banerjee et al. (2010), and explore the parameter space around the observed values to get an idea of the variation in the calculated scale height. We show that while the presence of gas constrains the stellar disk thickness, it is the dense, compact dark matter halo which plays a decisive role in determining whether the disk is thin.

Our earlier studies where the vertical thickness of the neutral H I gas was used to constrain the shape and density profile of the dark matter halo modeled as pseudo-isothermal spheres revealed an interesting feature, namely that large ordinary spirals like the Galaxy and M31 have non-compact halos while the superthin galaxy UGC 7321 has a compact halo (§2.2). This has prompted us to investigate here if in general a dense, compact halo plays a crucial role in determining the superthin distribution in a stellar disk.

The paper has been organized as follows. In §2, we present the numerical calculations, definitions of the terms and input parameters used, in §3 the results, followed by discussion and conclusions in §4 and §5 respectively.

2 NUMERICAL CALCULATIONS & DEFINITION OF TERMS USED

2.1 Numerical Calculations

We use the two-component model of gravitationally-coupled stars and H I gas in a galactic disk in the field of a pseudo-isothermal dark matter halo. In this model, the stars and gas are assumed to be present in the form of concentric, thin, axisymmetric disks embedded within each other, and are in a hydrostatic equilibrium in the z direction (Narayan & Jog 2002b, Banerjee & Jog 2008). We use the galactic cylindrical co-ordinates (R , ϕ and z).

The joint Poisson equation for the above two-component disk and halo is given by:

$$\frac{1}{R} \frac{\partial}{\partial R} (R \frac{\partial \Phi_{total}}{\partial R}) + \frac{\partial^2 \Phi_{total}}{\partial z^2} = 4\pi G (\sum_{i=1}^2 \rho_i + \rho_h) \quad (1)$$

where Φ_{total} is the net potential due to the stars, the H I gas and the dark matter halo; ρ_i with $i = 1$ to 2 denotes the mass volume density for each of the disk components (stars, and H I gas), while ρ_h denotes the same for the pseudo-isothermal halo. The halo density profile is given by (Binney & Tremaine 1987):

$$\rho_h(R, z) = \frac{\rho_0}{1 + \frac{R^2 + z^2}{R_c^2}} \quad (2)$$

where ρ_0 is the central density and R_c is the core radius of the halo.

The equation of hydrostatic equilibrium for the i^{th} disk component in the z direction is given by (Rohlf 1977):

$$\frac{\partial}{\partial z} (\rho_i < (v_z^2)_i >) + \rho_i \frac{\partial \Phi_{total}}{\partial z} = 0 \quad (3)$$

On combining the above two equations, we get the equation for the vertical equilibrium for each component of the disk to be:

$$\langle v_z^2 \rangle_i \frac{\partial}{\partial z} \left[\frac{1}{\rho_i} \frac{\partial \rho_i}{\partial z} \right] = -4\pi G (\sum_{i=1}^2 \rho_i + \rho_h) + \frac{1}{R} \frac{\partial}{\partial R} (v_{rot}^2(R))_{obs} \quad (4)$$

Here $\langle v_z^2 \rangle_i$ is the mean square velocity of the i^{th} disk component, and $(v_{rot})_R$ is the observed rotational velocity at any R . The last term is the radial part of the Laplacian. For a flat rotation curve this is identically equal to zero at the mid-plane, and for a nearly flat curve it changes the vertical scale heights less than 1% and hence can be ignored (Narayan et al. 2005). However, for a region of rising rotation curve as in dwarf galaxies, including this term can increase the scale heights by about 15 % (Banerjee et al. 2011), so we include it here for the calculations for HoII (Section 3.2). For UGC 7321, we have not included the radial term in the calculations to be consistent with our earlier work (Banerjee et al. 2010), the results of which such as ρ_0 and R_c have been used as input parameters in the current paper. The error in the calculated scale height is estimated to be ~ 22 %, thus even if this term were to be included, we would still get a superthin distribution for UGC 7321.

Therefore, we have two coupled non-linear, second-order ordinary differential equations in the variables ρ_{stars} and ρ_{gas} . These are solved numerically using the fourth-order Runge-Kutta method of integration in an iterative fashion, using suitable initial conditions (for details see Narayan & Jog 2002b, Banerjee & Jog 2008). The stellar density is obtained as a function of z at each galactocentric radius R , and the half-width-at-half-maximum (HWHM) defines the vertical thickness at each R .

2.2 Definitions of Terms Used

A superthin galaxy : In this paper we use the ratio z_0/R_D where z_0 is the vertical stellar scale height as in $\rho = \rho_0 \text{Sech}^2(z/z_0)$ and “ R_D ” is the exponential stellar disk scale length as the quantitative index of the stellar disk thickness following the work of Reshetnikov et al. (2003) and Bizyaev & Kajsin (2004). At each R , z_0 is obtained from the corresponding HWHM using a simple conversion factor ($z_0 = \text{HWHM} / 0.88$). We refer to a galaxy as being superthin if the average value of z_0/R_D within $R \leq 3R_D$ is ≤ 0.1

Dense and compact Halo: In this work, we define the dark matter halo as being “dense” if the central density ρ_0 is \sim a few times $0.01 \text{ M}\odot\text{pc}^{-3}$ or more. Ordinary large spirals like the Galaxy ($\rho_0 \sim 0.033 \text{ M}\odot\text{pc}^{-3}$; Narayan et al. 2005), M31 ($\rho_0 \sim 0.011 \text{ M}\odot\text{pc}^{-3}$; Banerjee & Jog 2008), and the superthin galaxy UGC 7321 ($\rho_0 \sim 0.035 - 0.057 \text{ M}\odot\text{pc}^{-3}$; Banerjee et al. 2010) thus have dense halos. Similarly, we label the halo to be “compact” if the core radius $R_c \leq 2R_D$. The high surface brightness (HSB) galaxies are found to have non-compact or extended halos with $R_c \geq 2R_D$ (Gentile et al. 2004). This is confirmed for our Galaxy where $R_c/R_D \sim 2.8$ (Narayan et al. 2005), and M31 where $R_c/R_D \sim 3.9$ (Banerjee & Jog 2008). The superthin galaxy UGC 7321, on the other hand, has been shown to have a compact dark matter halo with $R_c/R_D \sim 1.2 - 1.4$ (Banerjee et al. 2010). In contrast, the dwarf irregular galaxy such as HoII studied in §3.2 here, has less dense and extended halo, with $\rho_0 = 0.0009 \text{ M}\odot\text{pc}^{-3}$ and $R_c/R_D \sim 8.3$.

2.3 Input Parameters Used

We choose UGC 7321 as a prototypical example for our study as it is one of the very few superthin galaxies reasonably well studied observationally (§1), and all the required

input parameters for our model are available, as indicated in Table 1. The choice of stellar vertical velocity used is discussed next in some detail, since the stellar thickness depends crucially on this. The vertical stellar dispersion was measured by Matthews (2000) indirectly by assuming pressure equilibrium along the vertical direction for a stellar component alone. From the observed surface density (obtained from the luminosity and a M/L ratio) and the scale height for stars, and using eq. (7) in Matthews (2000), the central value of the vertical velocity dispersion is obtained to be 14.3 km s^{-1} (Banerjee et al. 2010). Here for consistency, we use the same value since we use the values of the halo parameters derived in Banerjee et al (2010) which were based on this dispersion value. We note that even the addition of gas and dark matter densities (from Fig. 3, Banerjee et al. 2010) will increase the central stellar dispersion by only $\sim 20\%$ to 17.0 km s^{-1} . We check that the resulting error in the calculated scale height is then 21 % and the calculated disk continues to be a superthin one.

We assume that the velocity dispersion falls off exponentially with a scale length, R_v , equal to $2R_D$. The measurement of disk scale length in an edge-on galaxy could be affected by the dust extinction which could be uneven or patchy. We have taken $R_D = 2.1$ as measured in R-band (Matthews 2000) which is therefore not too affected by the dust extinction. The K-band value is a better indicator of the true underlying stellar mass distribution, this was measured using the 2MASS data by Bizyaev & Mitronova (2002) who get a value that is not significantly different.

3 RESULTS

3.1 UGC 7321: A galaxy with a dense, compact halo

We now study the relative importance of the gas surface density with respect to a dense, compact dark matter halo in determining the vertical thickness of a stellar disk. Using our two-component model of a galaxy (see §2.1), we obtain the vertical scale height of the stars at each galactocentric radius R for UGC 7321, a galaxy with a superthin stellar disk.

In Figure 1, we plot the ratio z_0/R_D versus R for the stellar component in UGC 7321 for four different cases as indicated. These are the two-component model with the stars responding only to their own self-gravity i.e model excluding self-gravity of the gas and the gravitational field of the dark matter halo, model excluding only the gravitational field of dark matter, model excluding only the self-gravity of the gas, and lastly, the complete model including all the components i.e the self-gravity of the stars, the gas and the field of the dark matter halo. It is clear from the figure that the stellar disk of UGC 7321 qualifies as a superthin case by our definition ($z_0/R_D \leq 0.1$) only when the gravitational field of the dark matter halo is taken into account. This clearly illustrates the fact that although the self-gravity of the gas plays a role in reducing the vertical thickness of the stars as compared to that of the stars-alone case, it is the gravitational force due to the dark matter halo that is principally responsible in causing the stellar disk to be superthin.

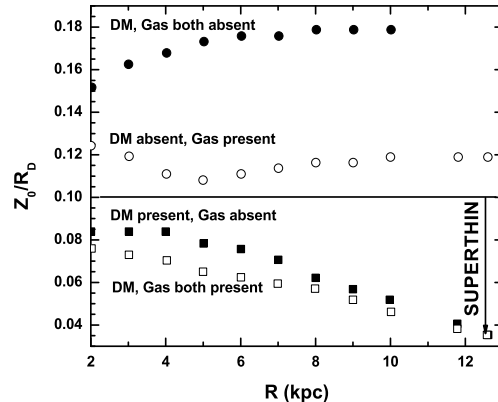


Figure 1. Plot of the ratio z_0/R_D (where z_0 is the stellar vertical scale height and R_D the exponential disk scale length) with galactocentric radius R for UGC 7321 for different realizations of the two-component galaxy model. From top to bottom, the curves correspond to the two-component model with both gas and dark matter absent, with gas present but dark matter absent, with gas absent but dark matter present, and with both gas and dark matter present respectively. Thus the ratio z_0/R_D is found to depend both on the gas and the dark matter halo components. For instance, at $R = 2 \text{ kpc}$, inclusion of gas (dark matter) reduces this ratio by $\sim 18\%$ (45%) to the value 0.124 kpc (0.084 kpc) as compared to the stars-alone case (0.152 kpc). However, this figure clearly shows that it is the dense, compact dark matter halo and not the gas-rich disk, that is responsible for the superthin stellar disk observed in UGC 7321.

In contrast, in the Galaxy the stellar disk is substantially more massive than in UGC 7321, hence the disk gravity dominates the vertical self-gravitational force, and the halo plays a minor role in determining the vertical stellar thickness in the inner Galaxy as was shown by Narayan & Jog (2002b). In the inner Galaxy, the rotation curve is mainly set by the disk, while in UGC 7321 the surface density of stars is much lower and hence stars contribute little to the radial gravitational force. Hence a dense and compact dark matter halo is also to explain the observed rotation curve in UGC 7321 as well.

In Figure 2, we study the importance of the compactness of the dark matter halo in determining the vertical thickness of the stellar disk in UGC 7321. Using our two-component model of gravitationally-coupled stars and gas in the field of a dark matter halo, but with the self-gravity of the gas set to zero, we obtain the average of z_0/R_D (averaged over $R \leq 3R_D$) for different values of the dark matter core radius R_c , for a given asymptotic value of the rotational velocity $v_{rot}(R = \infty) = 110 \text{ km s}^{-1}$ as set by the rotation curve from the relation $v_{rot}^2 = 4\pi G \rho_0 R_c^2$. This, in turn, makes the dark matter core density ρ_0 a function of the core radius R_c . Also, we choose a feasible range of trial values for R_c ($0.5R_D \leq R_c \leq 5R_D$) as indicated by earlier studies. The plot clearly brings out that a superthin stellar disk (average $z_0/R_D \leq 0.1$) results only when $R_c \leq 2R_D$ i.e when the dark matter halo is compact. We also study the relative importance of the gas surface density as compared to the compactness of the dark matter halo in this figure. Therefore also overlaid on this plot are horizontal lines indi-

Table 1. Input parameters of UGC 7321¹ and HoII²

Galaxy	$\Sigma_*(0)$ ($M_\odot \text{ pc}^{-2}$)	Σ_{Gas}^3 ($M_\odot \text{ pc}^{-2}$)	R_D (kpc)	σ_z^{HI} (km s^{-1})	$\sigma_z^{stars}(0)$ (km s^{-1})	ρ_0 ($M_\odot \text{ pc}^{-3}$)	R_c (kpc)	R_c/R_D
UGC 7321	50.2	4.1	2.1	9	14.3	0.057	2.5	1.38
HoII	27.8	9.8	1.2	7	11.1	0.0009	10.0	8.33

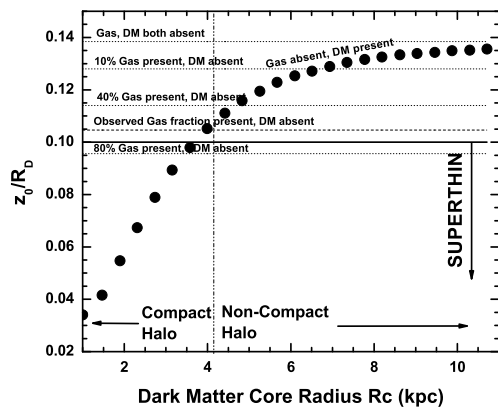
¹ Banerjee et al. 2010² Banerjee et al. 2011³ For $R \leq 3R_D$ 

Figure 2. Plot of the average value of the ratio z_0/R_D (where z_0 is the stellar vertical scale height and R_D the exponential disk scale length) as a function of the dark matter core radius R_c , here $R_D = 2.1$ kpc as in UGC 7321. From the plot it is clear that the stellar disk becomes superthin only for compact dark matter halos i.e. $R_c \leq 2R_D$. Also overlaid on this figure are horizontal cuts indicating the average z_0/R_D for cases with different gas surface density fractions but with that of the dark matter component set to zero. It is evident that in order to render the stellar disk superthin through a gas-rich disk only, the fraction of the gas surface density needs to be more ($\sim 70\%$ of that of the stars) than the observed value in UGC 7321 ($\sim 47\%$ within the region of interest i.e., $R \leq 3R_D$). This again confirms that a dense, compact dark matter halo is necessary for a superthin stellar disk.

cating the average value of z_0/R_D for different values of the gas to stellar surface density fraction, with the gravitational field due to the dark matter set to zero. This shows that in order to obtain a superthin stellar disk the gas fraction should be more than the the observed gas surface density in UGC 7321 in the region of interest. Therefore this figure again highlights the fact that a compact dark matter halo is necessary to obtain the superthin stellar disk in UGC 7321. Thus, only a high value of the relative mass of the dark matter halo can not be the reason behind the superthin stellar disk of a galaxy as claimed by Zasov et al. (2002). Instead the actual radial distribution of the dark matter is important.

Finally, we repeat the same calculations as above but with a central stellar surface density half of its original value to study the dependence of the vertical thickness of the stellar disk on the stellar surface density, as discussed in Bizyaev & Kajsin (2004). Most interestingly, even the case with the

gas surface density equal to the stellar surface density, fails to result in a thin stellar disk. In contrast, a highly compact halo with $R_c \leq 1.5R_D$ can render the stellar disk superthin even without any contribution from the gas component. Therefore, for low-mass galactic disks, a dense and compact dark matter halo plays the pivotal role in making the stellar disk superthin.

It may be appear that a very thin stellar disk could simply be explained by a low vertical dispersion and hence lower pressure support. There is indeed reason to believe that the stellar dispersion could be lower in the superthin galaxies since the various dynamical processes for heating the stellar dispersion are not effective (Section 4). However, from the results in Figures 1 and 2, we can argue that the low dispersion alone cannot be responsible for the superthin nature of UGC 7321. In absence of the dark matter, the disk is thick enough (with an average z_0/R_D well above 0.1) so that it will not be considered to be a “superthin” galaxy (See Fig. 1). Further, Figure 2 shows that for the given observed stellar velocity dispersion, the disk shows a “superthin” distribution only when the dark matter halo is compact (with $R_c/R_D < 2$). Thus a low stellar dispersion cannot be the main reason for the superthin distribution.

3.2 Comparison with HoII, a dwarf galaxy with a non-compact halo

In order to illustrate further the relative importance of a dense, compact dark matter halo and a gas-rich disk in determining the stellar disk thickness in realistic cases, we next apply our two-component model of the galaxy to obtain the average z_0/R_D for the stars in the dwarf irregular galaxy HoII chosen from the THINGS sample. HoII is gas-rich with the gas surface density dominating the disk dynamics on an equal footing with the stars. However the dark matter halo is neither dense ($\rho_0 = 0.0009 M_\odot \text{ pc}^{-3}$) and nor compact ($R_c/R_D \sim 8.3$). The input parameters required for our calculations are presented in Table 1. The central stellar velocity dispersion has been measured to be 11.1 km s^{-1} (Banerjee et al. 2011), using the approach as in Leroy et al. (2008). The dispersion is assumed to fall off exponentially with radius with a scale length equal to $2R_D$. In Table 2, we compare the resulting average z_0/R_D for HoII with that of UGC 7321 for different cases. Interestingly, the dense, compact halo of UGC 7321 can reduce its average z_0/R_D by 50% compared to the value of the stars-alone case. The non-compact halo of HoII, on the other hand, can reduce the stars-alone value by 10% only. Inclusion of gas to the stars-alone case, on the other hand, reduces the same by 18% and

Table 2. Average z_0/R_D for UGC7321 and HoII

Model	UGC7321	HoII
DM, & Gas both absent	0.138	0.374
DM absent, Gas present	0.113	0.166
DM present, Gas absent	0.070	0.335
DM present, Gas present	0.068	0.132

56% respectively. Therefore although the highly gas-rich disk of HoII is as effective as the dense, compact halo in reducing the disk thickness, it cannot, however, make the stellar disk superthin. This result corroborates our observation in §3.1 that in a low-mass disk, only a dense, compact dark matter halo can render the disk superthin.

Before concluding this section, we note that although each of the above two galaxies constitutes a typical representative of their respective galaxy class, namely UGC 7321 for the superthin LSBs and HoII for the dwarf irregulars, the values of the physical parameters would vary from galaxy to galaxy even within the same class of galaxy. Nevertheless varying the relevant input parameters around the realistic values seen in these prototypes and studying the effect on the stellar disk thickness helps us to follow the underlying trend, thereby providing useful pointers for future research.

3.3 Physical basis of a compact halo leading to a superthin stellar disk

For a dark matter-dominated galactic disk, the vertical thickness of the stars at any radius R is regulated by the dark matter mass density ρ_h close to the midplane ($z = 0$), or rather, by the steepness of its density profile. This is because the stars effectively respond as test particles to the dominant mass component of the disk, which is the dark matter halo in this case. Now the steepness of the density profile in the vertical direction is given by its first derivative with respect to z i.e $d\rho_h/dz$ which is zero at $z = 0$ for the pseudo-isothermal dark matter halo. So we use the second-derivative to quantify the steepness of the density profile. Simple calculations show that for a given value of the asymptotic rotational velocity, the second-derivative of the dark matter density ρ_h at any R is given by $d^2\rho_h/dz^2 \sim 1/(R_c^2 + R^2)^2$. Therefore a small value of R_c will result in a high value of $d^2\rho_h/dz^2$. In other words, a compact dark matter halo will result in a steep vertical density profile of the dark matter halo, and therefore, of the stars, which is equivalent to a thin stellar disk.

4 DISCUSSION

1. Results for a slower fall-off in stellar dispersion : In the calculations above, it was assumed that the vertical velocity dispersion falls exponentially with radius with a scale length, R_v , that is twice the scale length of the disk exponential surface brightness, R_D (or, $R_v/R_D = 2$). This standard relation was obtained for a single-component disk of constant thickness (van der Kruit & Searle 1981). In an earlier work (Narayan & Jog 2002a) it was shown that the observations of luminosity profiles when looked at closely do not imply

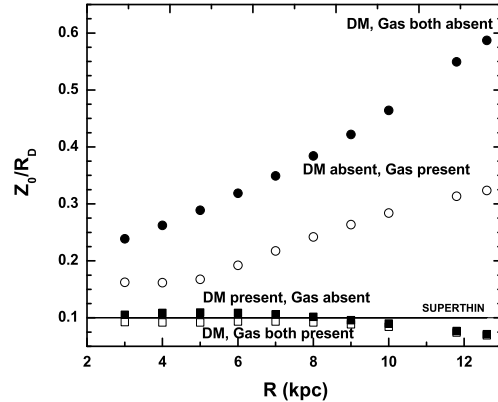


Figure 3. Plot of the ratio z_0/R_D versus galactocentric radius R for UGC 7321 for different realizations of the two-component galaxy model (as in Figure 1), but with a more gradual fall-off with radius in the stellar vertical velocity dispersion (as given by $R_v/R_D = 2.5$). As expected, the scale height values are higher here due to the higher pressure support from the stellar component. Nevertheless, the two main features of Figure 1 still remain: namely, the disk is still superthin (with the average $z_0/R_D < 0.1$ for radii within $< 3R_D$); and the main deciding factor whether the disk is thin is the compact dark matter halo (and not the gas), as can be seen by comparing the two curves that include the dark matter to those without it.

rigorously constant thickness, indicate a moderate flaring of stellar thickness, by a factor of few within the optical radius. This issue was studied for a multi-component disk in a dark matter halo, and comparing the model results with observations of luminosity profiles, it was shown that the ratio R_v/R_D lies in a range of 2-3 (Narayan & Jog 2002a).

Choosing a typical value of 2.5 in this range, we next repeat the calculation - see Figure 3 for the results. We find that for this higher ratio, the fall off in stellar velocity dispersion is slower, hence the resulting z_0/R_D values are higher especially at larger radii as expected (see Figure 3). Nevertheless, the two main features of Figure 1 still remain. First, the disk is still superthin (with the average $z_0/R_D < 0.1$ for radii $< 3R_D$). Second, the main deciding factor for the superthin nature of the disk is the compact dark matter halo (and not the gas), as can be seen by comparing the two curves that include the dark matter to those without it. Thus our main result from this paper, namely that a compact halo is the principal determining factor that determines the disk thickness, remains valid even for a higher value of R_v/R_D that was indicated by an earlier study (Narayan & Jog 2002a).

2. Evolution of disk thickness : Galaxy interactions are now known to be common, and these tend to increase the thickness of stellar disk with time (§1). Interestingly, the LSBs are known to lie in a region of low galaxy number density (Karachentsev 1999). The analysis of SDSS data shows these to lie along the edges of voids (Rosenbaum et al. 2009). This lack of galaxy interactions could explain why superthin galaxies retain their very thin stellar disk distribution over time. Bars and spiral features can thicken a stellar disk (Saha et al. 2010), but UGC 7321 has no detectable bar (Pohlen et al. 2004), and LSBs generally lack spiral features (de Blok

2006). So this mode of disk thickening does not apply in this case. Also, bending instabilities that could lead to disk thickening may also not be effective in presence of a dominant dark matter halo (Zasov et al. 1991). Thus the various dynamical processes that could cause a disk thickening are ineffective for the LSB galaxies. Hence, if the stellar disk is superthin to begin with, that property remains unchanged with time.

2. Origin of a dense, compact dark matter halo : The main underlying question from this work is: what decides whether the dark matter halo is dense and compact? Does the presence of a disk in it affect its internal evolution via angular momentum transfer? It is still not clear why two disks with otherwise similar properties (in terms of the stellar surface density and gas fraction) but with different halo properties give a superthin stellar disk (as in UGC 7321) or a puffed up disk (as in HoII). We hope that the result in present paper will trigger further research involving high resolution simulations of galaxy evolution that could address this issue.

5 CONCLUSIONS

We attribute the superthin nature of the stellar disk seen in some low surface brightness galaxies to the presence of a dense and *compact* dark matter halo. We obtain the stellar disk thickness for gravitationally coupled stars and gas in the presence of a dark matter halo. By studying the parameter space around the observed values for the superthin galaxy UGC 7321, we show that while the inclusion of gas in the problem does constrain the stellar disk thickness, the superthin distribution is mainly attributed to a dense, compact dark matter halo which dominates the disk from the inner radii of the galaxy. Thus a compact dark matter halo plays a crucial role in determination of the structure and dynamics of superthin galaxies. The question that needs to be addressed is what gives rise to such dense and compact dark matter halos to begin with during the galaxy evolution phase. Since superthin low surface galaxies constitute the prototypes of the high redshift galaxies in the local universe, our result may have important implications for galaxy formation and evolution models.

ACKNOWLEDGMENT

We thank Lynn Matthews, Aparna Maybhate, Paola Di Matteo and Rajaram Nityananda for useful discussion on related projects.

REFERENCES

Banerjee, A., & Jog, C. J. 2007, *ApJ*, 662, 335
 Banerjee, A., & Jog, C. J. 2008, *ApJ*, 685, 254
 Banerjee, A., Matthews, L. D., & Jog, C. J. 2010, *New A*, 15, 89
 Banerjee A., Jog, C. J., Brinks, E., & Bagetakos, I. 2011, *MNRAS*, 415, 687
 Binney, J., & Tremaine, S. 1987, *Galactic Dynamics*. Princeton Univ. Press, Princeton, NJ

Bizyaev, D., & Mitronova, S. 2002, *A&A*, 389, 795
 Bizyaev, D., & Kajsın, S. 2004, *ApJ*, 613, 886
 Dalcanton, J., & Bernstein, R. A. 2002, *AJ*, 124, 1328
 de Blok, W.J.G. 2006, in *Encyclopedia of Astronomy & Astrophysics*, P. Murdin, Ed., (Bristol: IOP), p. 1
 Gentile, G., Salucci, P., Klein, U., Vergani, D., & Kalberla, P. 2004, *MNRAS*, 351, 903
 Gilmore, G., & Reid, N. 1983, *MNRAS*, 202, 1025
 Goad, J.W., & Roberts, M.S. 1981, *ApJ*, 250, 79
 Karachentsev, I. 1989, *AJ*, 97, 1566
 Karachentsev, I. 1999, *Astr.L.*, 25, No.5, 318
 Kautsch, S.J. 2009, *PASP*, 121, 1297
 Leroy, A. K., Walter, F., Brinks, E., Bigiel, F., de Blok, W. J. G., Madore, B., Thornley, M. D. 2008, *AJ*, 136, 2782
 Matthews, L. D., van Driel, W., & Gallagher, J. S. 1999, *AJ*, 118, 2751
 Matthews, L. D. 2000, *AJ*, 120, 1764
 Matthews, L. D., & Wood, K. 2003, *ApJ*, 593, 721
 McGaugh, S.S., & de Blok, W.J.G. 1998, *ApJ*, 499, 41
 Narayan, C. A., & Jog, C. J. 2002a, *A&A*, 390, L35
 Narayan, C. A., & Jog, C. J. 2002b, *A&A*, 394, 89
 Narayan, C. A., Saha, K., & Jog, C. J. 2005, *A&A*, 440, 523
 Pohlen, M., Balcells, M., & Matthews, L.D. 2004, *ASSL*, 319, 791
 Qu, Y., Di Matteo, P., Lehnert, M.D., & Van Driel, W. 2011, *A&A*, 530, A10
 Reshetnikov, V. P., Dettmar, R.-J., & Combes, F. 2003, *A&A*, 399, 879
 Rohlfs, K. 1977, *Lectures on Density Wave Theory* (Berlin: Springer-Verlag)
 Rosenbaum, S.D., Krusch, E., Bomans, D.J., & Dettmar, R.-J. 2009, *A&A*, 504, 807
 Saha, K., Tseng, Y.-H., & Taam, R.E. 2010, *ApJ*, 721, 1878
 Uson, J.M., & Matthews, L. D. 2003, *AJ*, 125, 2455
 van der Kruit, P.C., & Searle, L. 1981, *A&A*, 95, 105
 Velazquez, H., & White, S.D.M. 1999, *MNRAS*, 304, 254
 Walker, I.R., Mihos, J.C., & Hernquist, L. 1996, *ApJ*, 460, 121
 Zasov, A.V., Makarov, D.I., & Mikailhova, E.A., 1991. *Soviet Astron. Lett.* 17, 374
 Zasov, A.V., Bizyaev, D.V., Makarov, D. I., & Tyurina, N. V. 2002, *Astronomy Letters*, 28, 527